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Experimental Verification of Reaction Torque Control Based on Driver Sensitivity to Active Front Steering

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1. Introduction

In today's world, the effectiveness of electronic active control systems in stabilizing a vehicle's motion has been recognized; thus, numerous active control systems have been developed to realize effective braking torque and traction control and have been incorporated in mass-produced vehicles. However, an effective active control system for steering is not yet available. Active front steering (AFS) is an effective technique to stabilize the motion control when methods such as the Direct Yaw Control (DYC) are used; however, for a vehicle, it is difficult to resolve the problem of interference between driver steering and automatic steering with AFS. Some studies have verified that AFS is effective from the viewpoint of vehicle motion physics but such verification alone is insufficient. Since the driver has control of the steering wheel, driver sensitivity interferes with vehicle motion control, and the theoretical effect of control by AFS cannot be realized. This problem is known as the steering interference problem. Therefore, it is important to ensure that the active steering control system does not interfere with driver steering. In this paper, we evaluate driver sensitivity quantitatively using a steering device, and we verify the efficacy of the reaction torque control method based on the fundamental characteristics of driver sensitivity.

2. Active front steering

In traditional steering systems, due to the presence of mechanical parts such as the torsion bar spring and the intermediate shaft between the steering wheel and front axle wheel, the inclinations of both wheels are directly related to each other. For this reason, it is not possible to realize AFS in such conventional systems. Either of two techniques can be used to solve this mechanical problem: steer-by-wire (SBW) and differential steering. SBW allows the steering wheel and front wheels to be controlled independently by replacing mechanical units with electric signal lines. On the other hand, differential steering controls the differential angle between the steering wheel and front axle wheels using a particular gear such as a planetary gear or harmonic gear. However, with these techniques, the following problems must be overcome to realize AFS. Experimental verification particularly describes the problems at the chapter 4.

2.1 Problems with AFS when using a differential gear

Since this technique links the steering wheel to the front axle via a differential gear, the reaction torque of the disturbance from the road surface is directly transmitted to the driver. For this reason, this technique inevitably causes steering interference when AFS intervenes strongly during steering.

2.2 Problems with AFS when using Steer-By-Wire

Since this technique does not link the steering wheel to the front axle via mechanical components, the reaction torque from the road surface is not transmitted to the driver at all. For this reason, the technique can decouple the steering interference completely. This is an advantage for AFS. However, when the front wheels hit a bump in the road, or if the driver operates the vehicle on gravel, this technique cannot transmit the reaction torque as road information to the driver. This is a critical problem for safe driving.

For realizing an effective AFS system, it is important to control the reaction torque transmitted to the driver for safe operation. The purpose of our study was to evaluate driver sensitivity quantitatively, to propose novel techniques for controlling the reaction torque based on driver sensitivity, and to verify whether these techniques were effective by using a steering device.

2.3 Active front steering control

A planetary gear structure is shown in Fig. 1. It consists of sun gear, ring gear and carrier. Each gear is connected to steering axle, front wheel axle, and sub motor. The block diagram of a steering system using a planetary gear for AFS is shown in Fig. 2. The block diagram of the AFS control is shown in Fig. 3. State variables for this system are shown in Table 1. The angle equation is shown in (1). α is gear ratio determined by number of gear teeth. The sub motor controls the ring gear angle in the planetary gear shown in (2) for AFS. The AFS sets the angle $\Delta\theta$ between the steering wheel and the front axle wheel based on vehicle motion controller. As a result, the AFS controls the front axle wheel angle shown in (3). The equation is calculated using the equations (1) and (2). The main motor is used to reduce the steering load in order to assist the driver. The torque equation of the planetary gear is shown in (4). The torque is not relationship between the gear angle.

$$\theta_m = -\frac{\theta_f}{\alpha} + \frac{\alpha+1}{\alpha}\theta_s \quad (1)$$

$$\theta_m^* = \theta_s - \frac{\Delta\theta}{\alpha} \quad (2)$$

$$\theta_f = \theta_s + \Delta\theta \quad (3)$$

$$T_f = \frac{T_m}{\alpha} = -\frac{T_s}{1+\alpha} \quad (4)$$

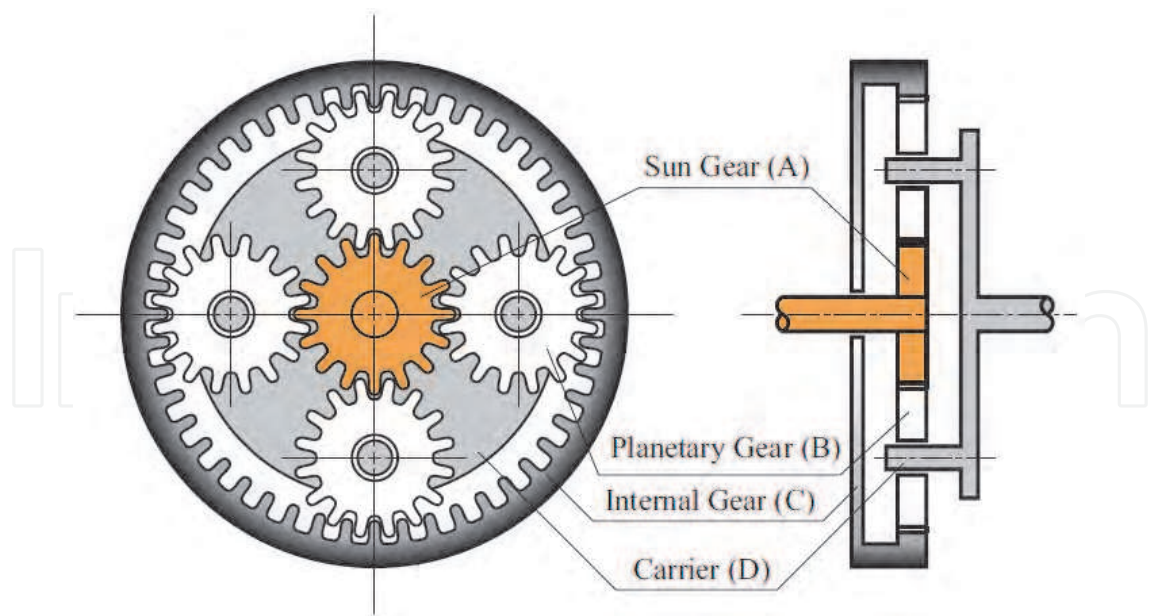


Fig. 1. A structure of planetary gear.

T_s	Steering wheel torque
T_d	Driver torque
T_r	Reaction torque to a driver
T_f	Front axle wheel torque
T_f^*	Front axle wheel reference torque
T_{RTRS}	Reaction torque from road surface
T_a	Power assist torque
θ_s	Steering wheel angle
θ_m	Ring gear angle
θ_m^*	Ring gear reference angle
θ_f	front axle wheel angle
θ_t	front wheel angle
$\Delta\theta$	Angle between steering wheel and front axle wheel
J_s	Steering wheel inertia
J_f	Front steering inertia
B_s	Friction coefficient of steering wheel
C_f	Friction coefficient of front steering
K_a	Power assist ratio
G_t	Gear ratio of rack and pinion

Table 1. Steering system parameters.

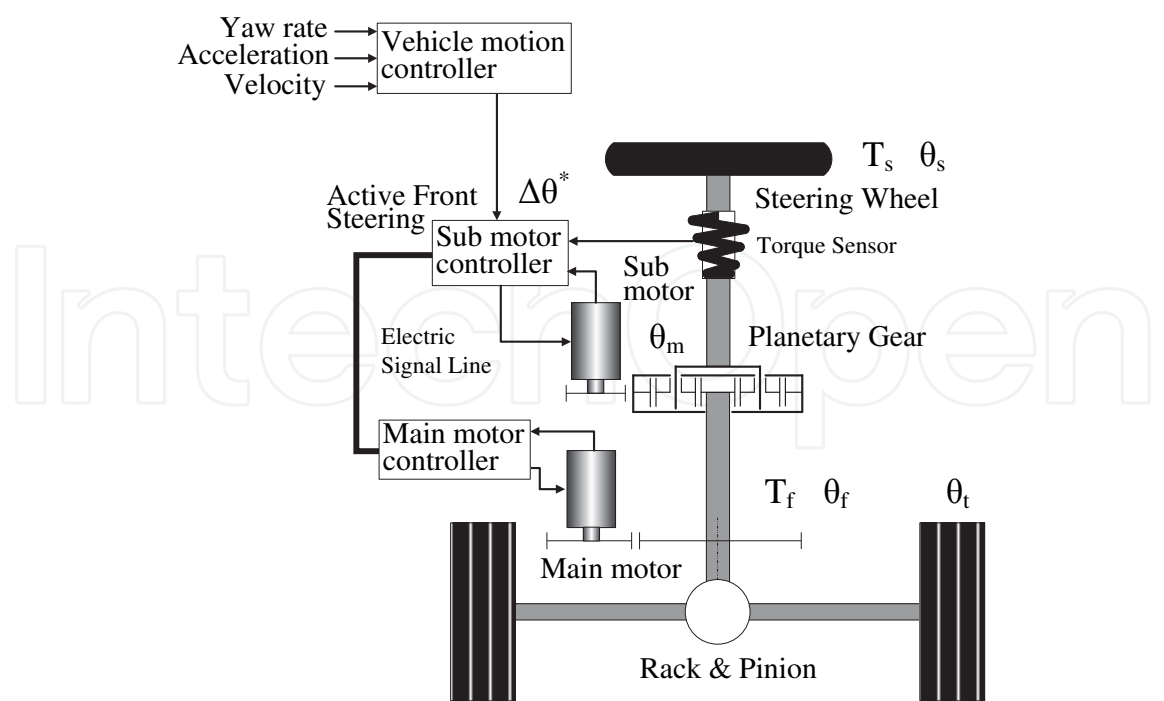


Fig. 2. Differential steering system.

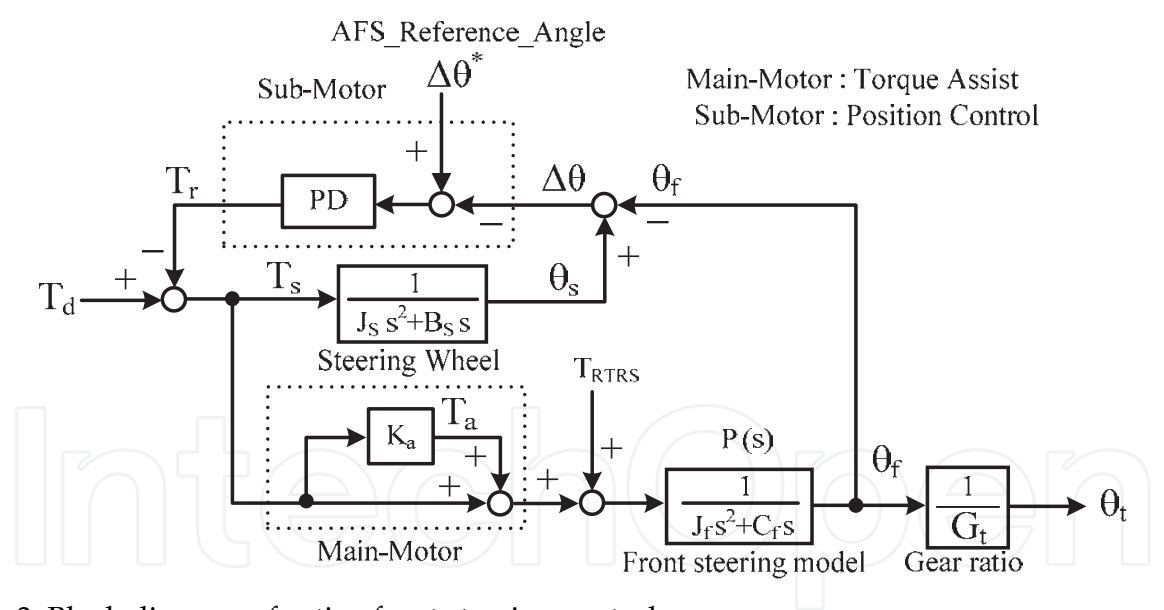


Fig. 3. Block diagram of active front steering control.

3. Method of experimental evaluation

We verified the following effects conclusively with a steering device shown in Fig.4. Firstly, evaluation of the response of the following differential angle to the reference differential angle by AFS. Block diagram of AFS is shown in Fig.2. If a motion control PC that supervises vehicle’s motion detects a dangerous movement such as a slip, the PC sends the differential angle reference to the PC controlling the steering system. The steering PC attempts to match the differential angle to the reference. This study evaluated the response.

Secondly, Evaluation for reducing the steering interference during AFS. This paper evaluated a way to reduce the steering interference that impedes driver steering during AFS operation.

Finally, Evaluation for transmitting the reaction torque required for safe driving. In order to realize driver safety, it is necessary to provide an appropriate reaction torque for the steering wheel. This study evaluated a way to transmit the reaction torque to the driver via the steering wheel.

3.1 Steering device

The AFS simulation was evaluated using the steering device. The photo of planetary gear our produced is shown in Fig. 5 and courtesy photograph of steering device around the planetary gear is shown in Fig. 6. The block diagram shown in Fig. 2. The state variable used in the block diagram is shown in Table 1. This device consisted of two motors and a planetary gear. The sub-motor controlled the planetary gear so that the differential angle $\Delta\theta$ matched the reference angle $\Delta\theta^*$ for AFS. $\Delta\theta$ is differential angle between the steering wheel and the front axle wheel angle. The main-motor was used to reduce the steering load to help the driver. The motor also simulated the reaction torque T_{RTS} that the road surface exerts on the front wheels. The equation for the reaction torque is shown in (5). This torque consists of self aligning torque (SAT) and the friction of the front wheels. It is transmitted in a direction opposite to that of the steering operation so that the driver does not turn the steering wheel excessively; thus, the torque is exerted to ensure safe driving. By using digital signal processor (DSP), this device can simulate AFS using SBW or a differential gear.

$$T_{RTS} = K_t\theta_t + C_t\dot{\theta}_t \quad (5)$$

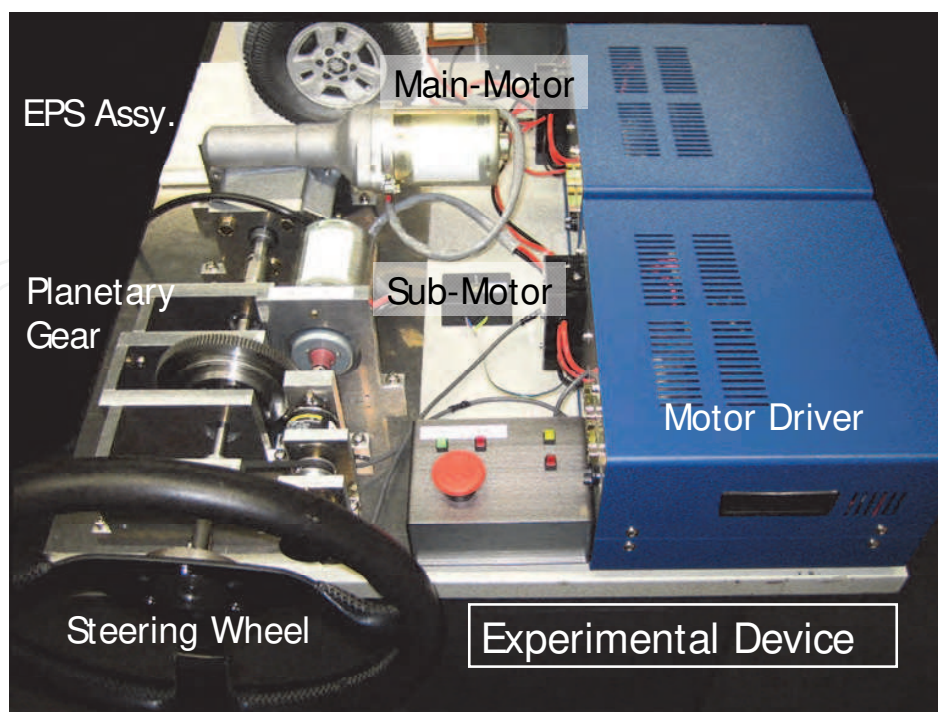


Fig. 4. Steering device.



Fig. 5. Planetary gear produced in Hori laboratory

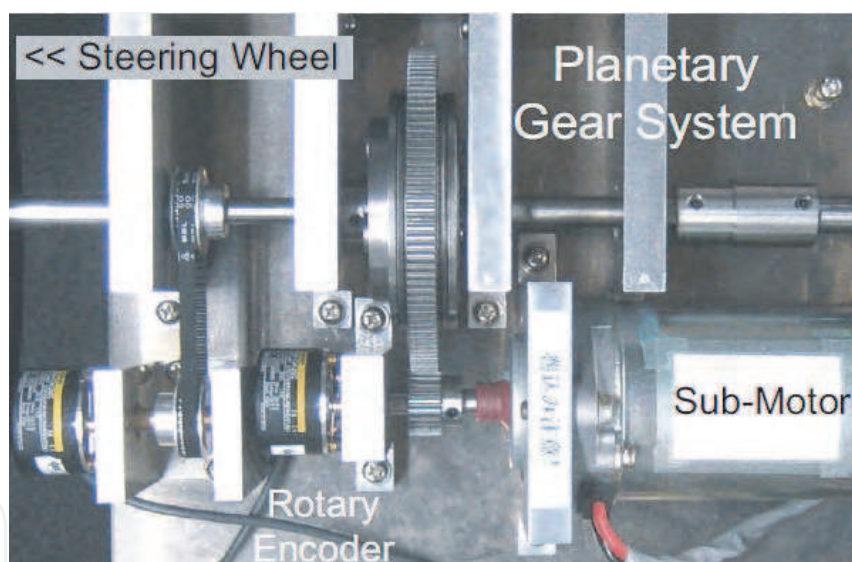


Fig. 6. Courtesy photograph of Steering device around the planetary gear

3.2 AFS simulation starting conditions

The experiment started when the steering wheel was turned to the left by 90° . After a few seconds, as soon as the motion control PC detected a slip in the vehicle, the AFS was activated. The AFS set the angle between the steering and front wheels to the reference angle $\Delta\theta^*$ calculated in the motion control PC. The experimental device simulated the reference angle, as shown in Fig. 7. For example, the AFS set the angle to -60° in the case of pattern 1, and passed on this value to the steering control PC. This means that the front wheel's angle was reduced by 30° in the steering control PC. Then, each angle is shown in Fig.8. In comparison with the angular velocity for pattern 1, that for pattern 5 was faster while that

for pattern 9 was slower. The device could simulate 12 types of patterns in an AFS experiment.

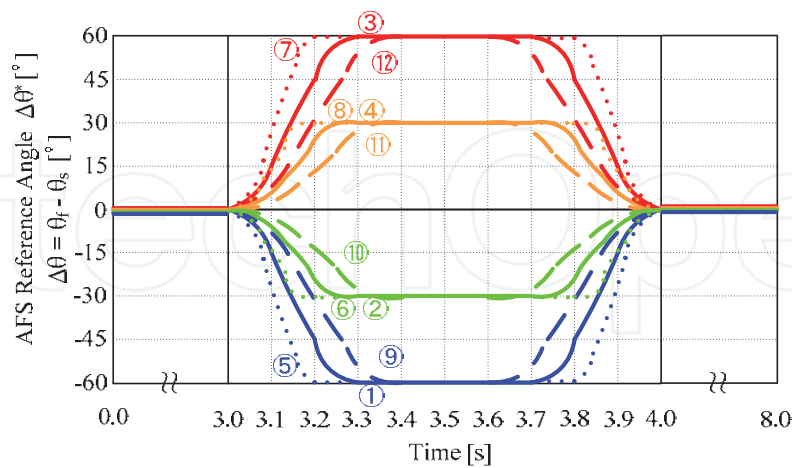


Fig. 7. Differential reference angle for AFS.

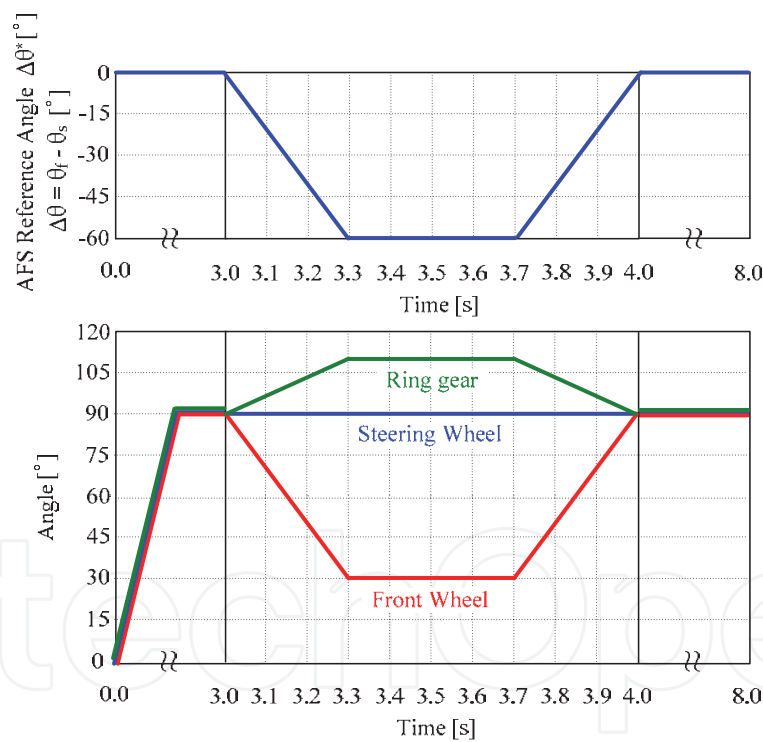


Fig. 8. Angle control for AFS.

4. Fundamental verification of driver sensitivity during afs operation

The verification revealed that driver steering sensitivity interfered with automatic steering control. Differential angle control was applied in the experiment. We performed the reference angle experiment using patterns 1 to 12, as shown in Fig. 7, and verified the effect of driver sensitivity. From the results, we proposed a reaction torque control method based on driver sensitivity.

4.1 Comparative verification of steering interference in differential angle

4.1.1 Pattern 1: reference angle $\Delta\theta^*=-60^\circ$

The experimental result of the reference angle based on pattern 1 is shown in Fig. 9. The graph of the angle shows that the control could achieve the differential angle (-60°) in 3 to 4 s when AFS was performed, but there were two problems. One problem was that the steering wheel angle was considerably turned toward the other side of the front axle wheel angle. This prevented the driver from perceiving the vehicle's motion. Another problem was that the control caused the steering torque to decrease rapidly. This shows that the reaction torque decreased rapidly and it prevented the driver from operating the vehicle safely. That is to say, AFS returned the front axle wheel angle and the angle became small. The reaction torque that the driver received from the road surface decreased and the driver perceived that the steering wheel became light. The driver turned the steering wheel increasingly by 100° . This is a problem known as steering interference by AFS. If the driver maintained the steering wheel angle of 90° , the front axle wheel angle should have returned to the original 30° . However, in the results, it only returned to 40° . This means that sufficient AFS control was unrealizable from the viewpoint of motion control.

4.1.2 Pattern 2: reference angle $\Delta\theta^*=-30^\circ$

The experimental result of the reference angle based on pattern 2 is shown in Fig. 10. The graph of the angle shows that the steering interference was less than the result of Fig. 9 since the front axle wheel angle was reduced to 60° and the steering angle was kept constant. As a result, the slope of the reaction torque that the driver received from the road surface was small. Therefore, it is advisable not to transmit the torque to the driver directly when the slope is excessively large. With regard to the steering axle, the reaction torque that would not cause steering interference is not more than 3 to 5 Nm/s.

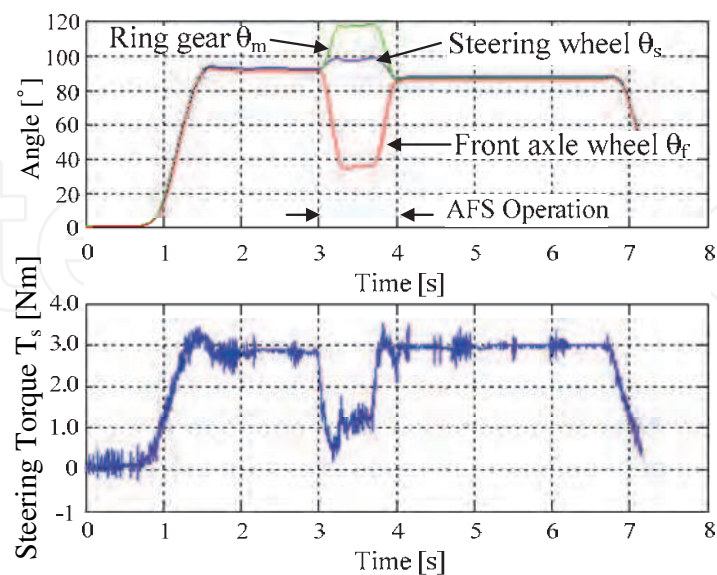


Fig. 9. Experimental result of reference angle based on pattern1.

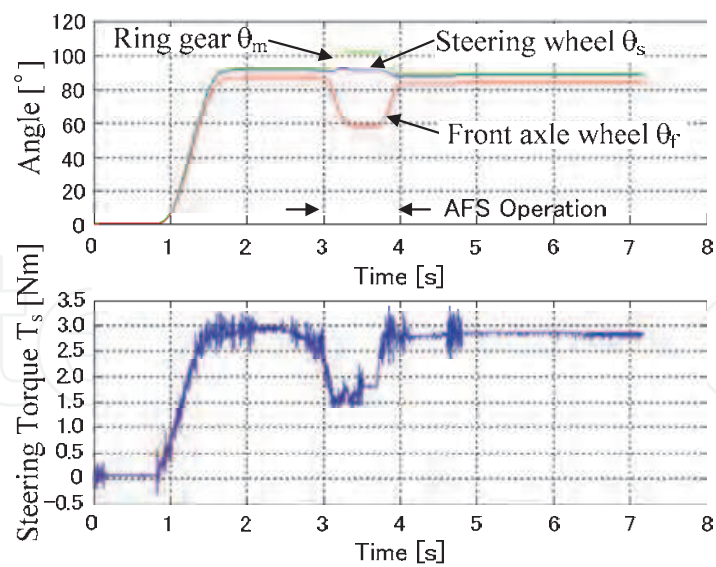


Fig. 10. Experimental result of reference angle based on pattern2.

4.1.3 Pattern 3: reference angle Δθ* = +60(°)

The experimental result of the reference angle based on pattern 3 is shown in Fig. 11. This result shows less steering interference than the result of Fig. 9. The result indicates that the driver sensitivity was insufficient to handle a reaction torque along a direction opposite to that of the torque that the driver received from the road surface before AFS operation.

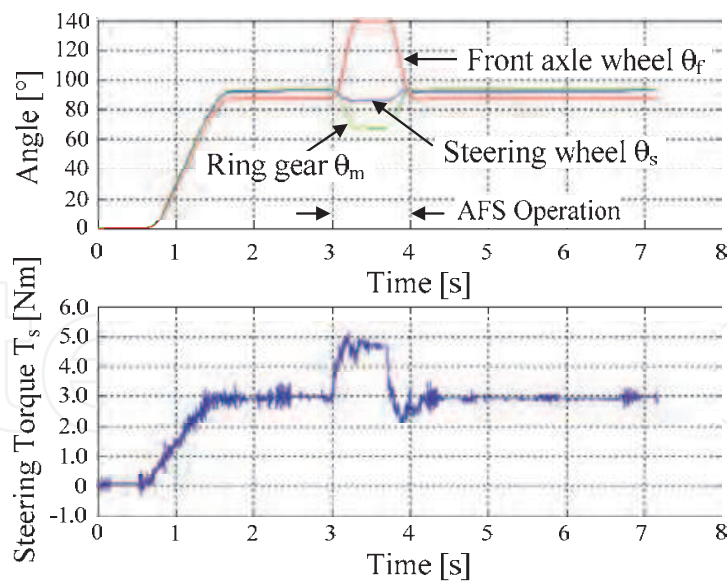


Fig. 11. Experimental result of reference angle based on pattern 3.

4.2 Comparative verification of steering interference in velocity of differential angle

The verification revealed that the velocity of the differential angle during AFS operation affected any steering interference caused by driver sensitivity.

4.2.1 Pattern 5: velocity of reference angle $\Delta\theta^*/dt = -300(^{\circ}/s)$

The angular velocity for pattern 5 was higher than that for pattern 1. The experimental result for the reference angle based on pattern 5 is shown in Fig. 12.

4.2.2 Pattern 9: velocity of reference angle $\Delta\theta^*/dt = -150(^{\circ}/s)$

The angular velocity for pattern 9 was slower than that for pattern 1. The experimental result of the reference angle based on pattern 9 is shown in Fig. 13.

A comparison of the experimental results for patterns 1, 5, and 9 revealed that a higher angular velocity in the front axle wheel led to greater steering interference. The driver received reaction torque in proportion to the velocity via the steering wheel. If the velocity was excessively high, the driver was unable to handle the torque and keep the steering wheel steady. Achieving safe AFS requires a torque to compensate for driver sensitivity to the velocity.

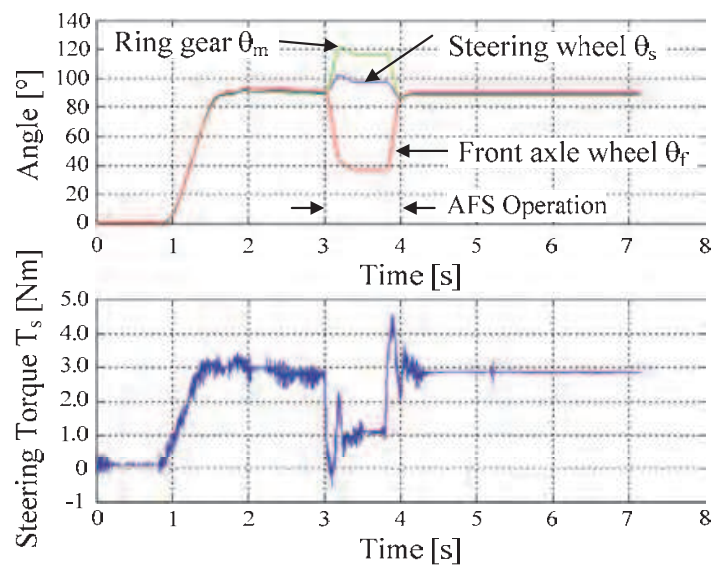


Fig. 12. Experimental result of reference angle based on pattern 5.

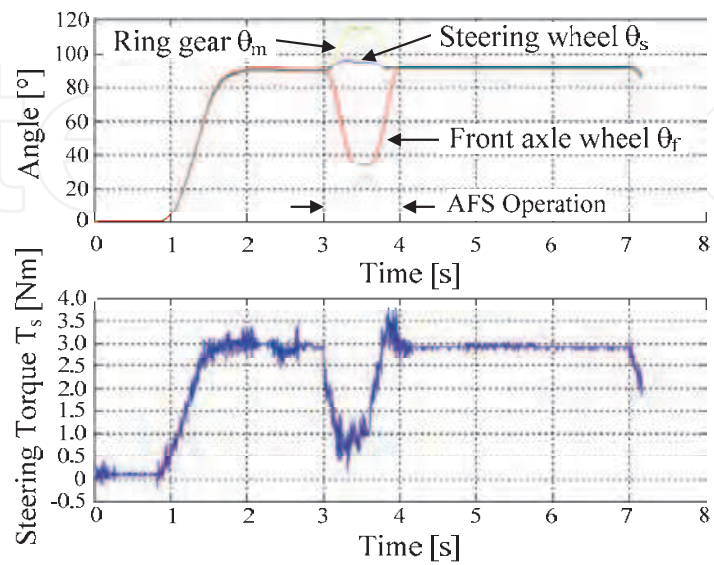


Fig. 13. Experimental result of reference angle based on pattern 9.

4.3 Reaction torque control based on idealized model with Steer-By-Wire

The block diagram of the control method is shown in Fig. 14. The control can decouple the steering interference completely by transmitting the reaction torque associated with the idealized model to the driver. Equation (6) for the reaction torque T_r shows that T_r is not associated in any way with the front wheels. The control can decouple the interference since the driver does not receive the AFS-modified reaction torque from the road surface. However, the driver loses the road information at the same time because there is no feedback from the front wheels to the steering wheel. Our control method realizes AFS by sending the reference angle of the front axle wheel to the front wheel controller, as shown in (7).

$$T_r = K_s \theta_s + C_s \dot{\theta}_s \quad (6)$$

$$\theta_f^* = \theta_s + \Delta\theta^* \quad (7)$$

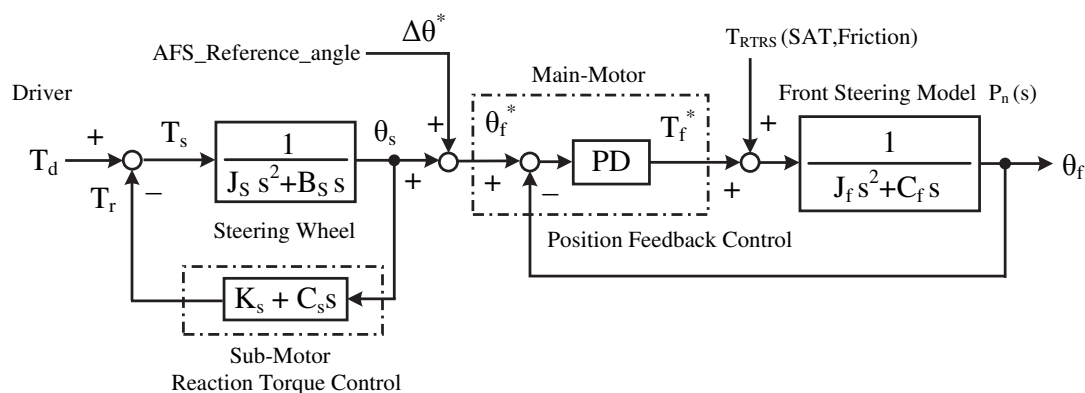


Fig 14. Block diagram of reaction torque control based on idealized model.

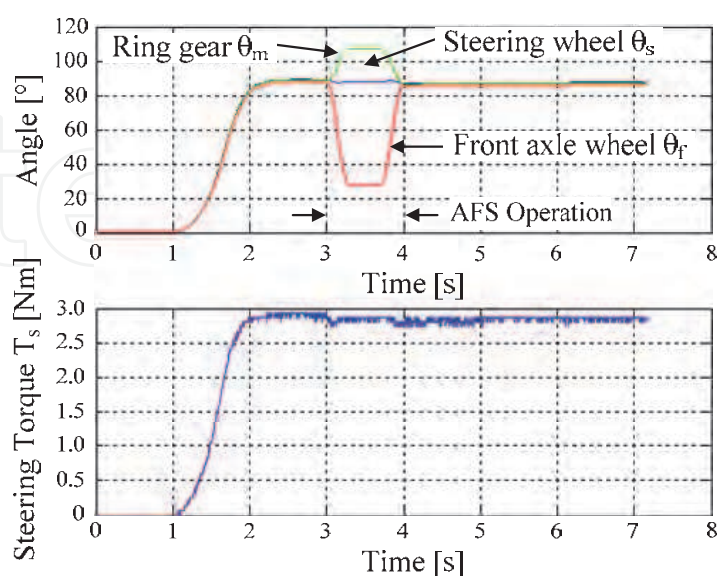


Fig. 15. Experimental result of AFS by reaction torque control based on idealized model with SBW.

The experimental results for this control are shown in Fig. 15. The graph of the angle shows that the front axle wheel angle returned to 30° , and the steering wheel angle was maintained constant angle at 90° . On the other hand, the steering torque shows that the driver constantly received a reaction torque. This control method did not cause any steering interference because no AFS-modified reaction torque was transmitted by the control from the road surface to the driver. Although this control method seems to be suitable, a problem encountered is that the driver operates the vehicle without receiving any reaction torque as road information when the front wheels hit a bump in the road or the driver operates the vehicle on a gravel road. In other words, the control can decouple the interference completely but at the same time it cannot provide reaction torque required for safe driving.

5. Reaction torque control based on driver sensitivity during afs operation

Since the differential steering always transmits the reaction torque from road surface to the driver, during AFS operation It led to steering interference. On the other hand, SBW could decouple the steering interference because no AFS-modified reaction torque was transmitted to the driver. However, it could not provide reaction torque as road information to the driver. Reducing steering interference and transmitting road reaction torque are inconsistency to each other. We propose two reaction torque control methods for a driver. First one is reaction torque control based on variable assist ratio control, another one is based on reaction torque observer and hysteresis torque control.

5.1 Reaction torque control based on variable assist ratio with differential steering

The block diagram of this method is shown in Fig. 3 and It controls assist ratio K_a based on differential angle between steering wheel and front axle wheel. This equation is shown in (8). K_{a0} is constant value. Reaction torque to a driver is shown in (9). Torque difference between steering angle and front axle wheel angle is transmitted to a driver. It is same as torque sensor with torsion bar spring for conventional EPS system. On the other hand, the equation of front axle wheel angle is shown in (10). It shows that the variable assist torque can comepeensates the reaction torque T_{RTRS} from road surface. Because the reaction torque depends on the front axle wheel angle as SAT. To the next, it compensats the front axle wheel angle. As a result, It can control the reaction torque transmitted to a driver.

$$K_a = (\theta_f / \theta_s) K_{a0} \quad (8)$$

$$T_r = (\theta_s - \theta_f) (K_p + K_D s) \quad (9)$$

$$\theta_f = \frac{[(1 + K_a) T_s + T_{RTRS}]}{J_f s^2 + C_f s} \quad (10)$$

5.2 Reaction torque control based on estimated reaction torque and driver sensitivity

As mentioned above, although the reaction torque control based on the idealized model with SBW can decouple the steering interference, a limitation of the control method is that the driver cannot use the reaction torque as road information. In an application based on this control method, the reaction torque must be measured or estimated to transmit this

information to the driver. In this study, we estimated the torque using an assist motor attached to the front axle wheel and an observer. In addition, we propose to adjust steering sensitivity by transmitting model reaction torque to a driver. Block diagram of this method is shown in Fig. 16.

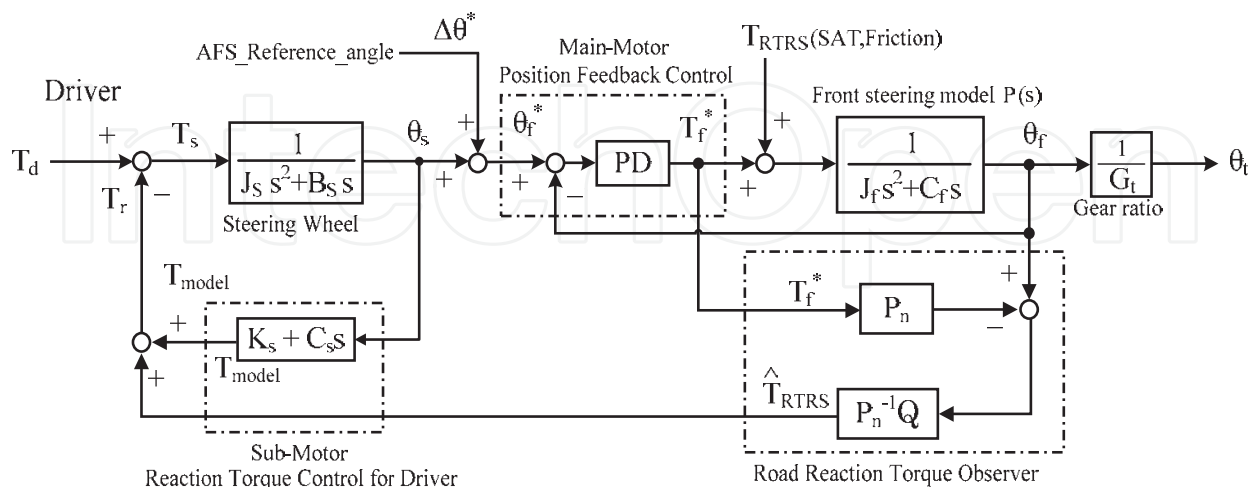


Fig. 16. Reaction torque control based on estimated reaction torque and driver sensitivity.

5.2.1 Reaction torque observer

The block diagram of the reaction torque observer is shown in Fig. 17. The reaction torque T_{RTRS} from the road surface is an unknown state variable to be estimated. First, the estimated angle of the front axle wheel, $\hat{\theta}_f$, is calculated using the nominal model $P_n(s)$ of plant $P_n(s)$ and the reference torque of the front axle wheel, T_f^* , which are known state variables. Second, $\Delta\theta$ is calculated as the difference between the estimated value $\hat{\theta}_f$ and the measured value θ_f . \hat{T}_{RTRS} is calculated by means of the inverse model P_n^{-1} of the plant. Since P_n^{-1} is not a proper function, \hat{T}_{RTRS} is calculated using a low-pass filter Q . If the reaction torque \hat{T}_{RTRS} estimated by the observer were to be directly transmitted to the driver, the control system would cause steering interference in the same manner as the conventional angle control, as shown in Fig. 9. Therefore, it is necessary to adjust the gain and frequency of \hat{T}_{RTRS} with the low-pass filter Q . The formula is shown below.

$$\theta_f = (T_f^* + T_{RTRS})P(s) \quad \hat{\theta}_f = T_f^* \cdot P(s) \quad (11)$$

$$\hat{T}_{RTRS} = (\theta_f - \hat{\theta}_f)P_n^{-1}(s) \cdot Q(s) \quad (12)$$

If the nominal model $P_n(s)$ is confirmed to be identical to plant $P(s)$, \hat{T}_{RTRS} is calculated by the following formula (13).

$$\hat{T}_{RTRS} = T_{RTRS}(s) \cdot Q(s) \quad (13)$$

$P(s)$ is identified using the Prediction Error Method based on the Maximum-Likelihood Method.

Low pass filter Q reduces higher frequency gain than cut-off frequency $1/\tau_q$. τ_q is time constant value. In this paper, cut-off frequency $1/\tau_q$ is 20 (Hz) because reaction torque

required for steering operation is about 0-10 [Hz]. And feedback gain G_{fb} is adjusted by formula (15) to assist driver return the steering wheel. As a result, it is able to reduce the steering interference.

$$G(s) = \frac{G_{fb}}{1 + 2\tau_q s + \tau_q^2 s^2} \quad (14)$$

$$1 < G_{fb} < 1.5 \quad (15)$$

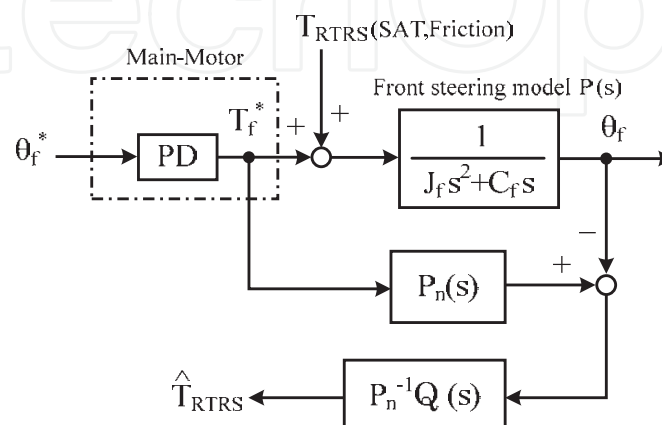


Fig. 17. Reaction torque observer.

5.2.2 Hysteresis torque control for varying steering sensitivity

This method compensates for driver sensitivity during the steering operation. To be specific, it controls hysteresis, which compensates for driver sensitivity. The sub-motor controls hysteresis by adjusting the coefficient C_s in proportion to the angular velocity of the steering wheel in Fig. 16. The model reaction torque shown in (16) controls steering sensitivity for driver. The coefficient C_s is determined by difference angle $\Delta\theta$ from the formula (17). When a driver operates the steering wheel angle of sine-wave at 0.5 [Hz], lissajous curve is drawn To evaluate the steering characteristics. This result is shown in Fig. 18. Blue line is $K_s = 2.0$, $C_s = 0.2$, red one is $K_s = 2.0$, $C_s = 0.6$. When the coefficient C_s is large, the hysteresis band is expanded. On the other hand, when comparing to frequency of steering torque in Fig.19, high frequency steering torque vibration is reduced. However, large hysteresis band strikes the driver as heavy steering feeling. For this reason, steering system need to adjust appropriately hysteresis band according to road reaction torque. When the reaction torque is changed using AFS, an appropriate hysteresis value enables the driver to maintain the operation and reduces the vibration of the steering torque and the steering interference. Because driver has not felt the vibration in the hysteresis band. The torque T_r transmitted to the driver is given by (18). In this paper, the stiffness K_s is zero because of compensating only steering vibration.

$$T_{model} = K_s \theta_s + C_s \dot{\theta}_s \quad (16)$$

$$K_s = \frac{K_t}{1 + K_a}, \quad C_s = \frac{C_t}{1 + K_a} \frac{d(\Delta\theta)}{dt} \quad (17)$$

$$T_m = \hat{T}_{RTRS} + T_{model} \quad (18)$$

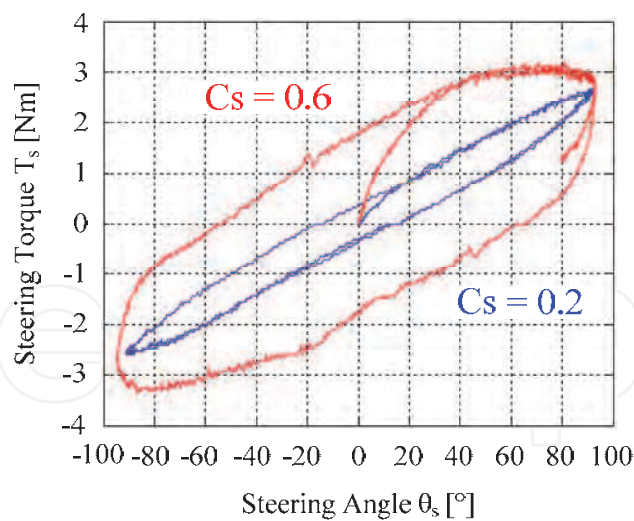


Fig. 18. Hysteresis band characteristic changed by viscous friction.

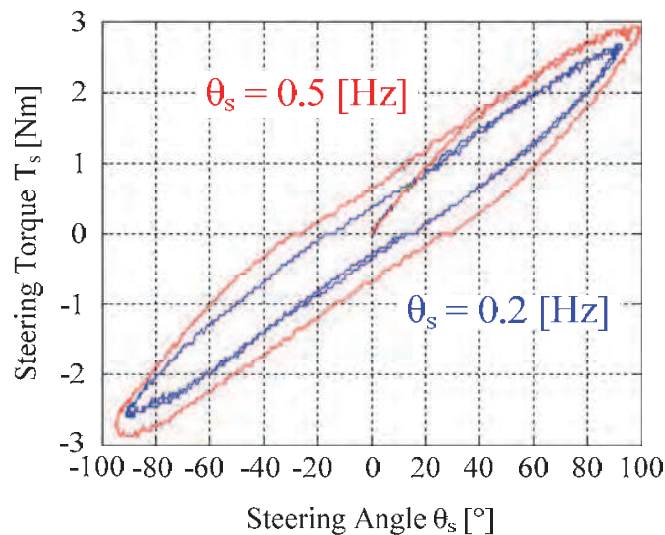


Fig. 19. Hysteresis band characteristic changed by angular velocity of steering wheel.

6. Experimental verification of AFS by proposed reaction torque control for steering

The experimental verification revealed that the proposed method was effective in allowing a driver to operate a vehicle safely with AFS. The reference angle of the AFS experiment was applied to patterns 1 and 5, which caused large steering interference at the experiment of 4th clause.

6.1 Reaction torque control based on variable assist ratio control

6.1.1 Pattern 1: reference angle $\Delta\theta^*=-60(^{\circ})$

The experimental result of the control is shown in Fig. 20. The steering torque shows that the reaction torque is more constant than the result of the differential angle control shown in Fig. 9. In the graph of the angle, the steering wheel angle has been kept constant angle at 90° and the front axle wheel angle was returned to 30° . As the two results, the control is an effective technique to reduce the steering interference during AFS operation.

6.1.2 Pattern 5: velocity of reference angle $\Delta\theta^*/dt = -300(^{\circ}/s)$

The experimental result is shown in Fig. 21. The steering interference has been reduced compared to that of differential angle control shown in Fig. 12. The front axle wheel angle has been returned to about 30° . However, the steering torque has been vibrated in 3.0-3.3(s) and 3.7-4.0(s). When the front wheel angle is returned quickly, road reaction torque contains larger vibration. Since this method compensates reaction torque in proportion to the front wheel angle, the reaction torque vibration could not be reduced sufficiently.

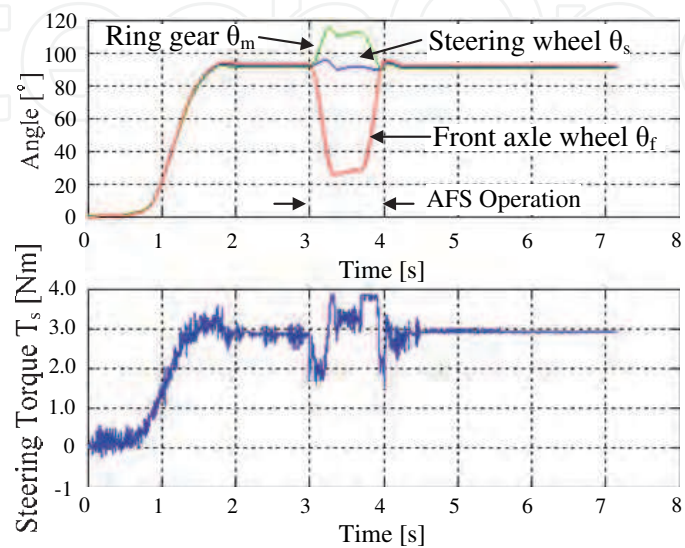


Fig. 20. Experimental result of AFS based on variable assist ratio control in case of pattern 1.

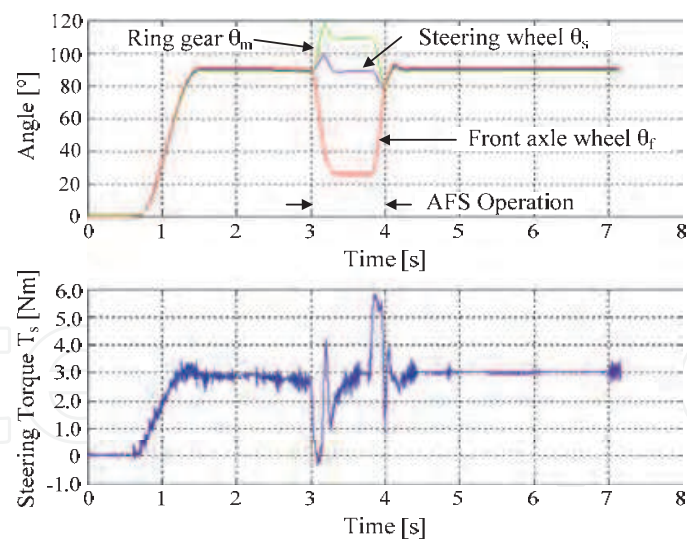


Fig. 21. Experimental result of AFS based on variable assist ratio control in case of pattern 5.

6.2 Reaction torque control based on estimated reaction torque and driver sensitivity

6.2.1 Pattern 1: reference angle $\Delta\theta^* = -60(^{\circ})$

The experimental result is shown in Fig. 22. The graph of the angle shows that the technique did not cause the same steering interference as the reaction torque control based on the idealized model shown in Fig. 15; in addition, the proposed technique exhibited excellent performance in matching the reference angle of the front axle wheel. On the other hand, the

graph of the steering torque shows that the technique could transmit a small amount of the reaction torque from the road surface to the driver.

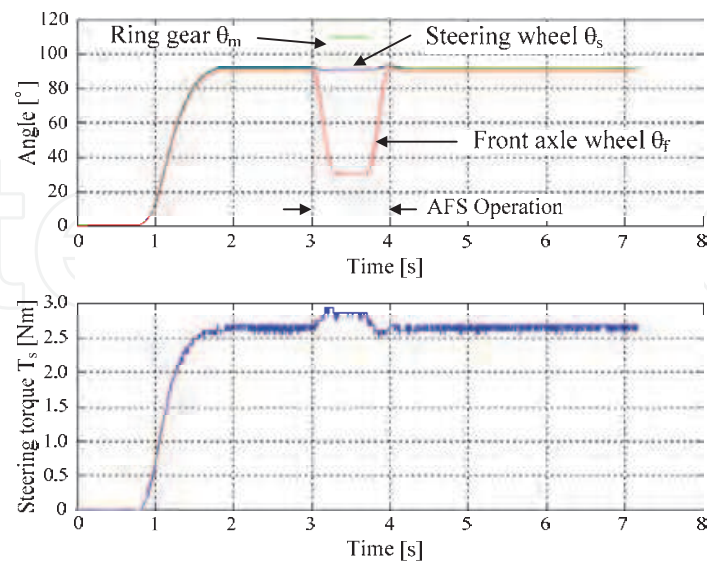


Fig. 22. Experimental result of AFS by reaction torque control based on driver sensitivity in case of pattern 1.

Thus, the technique was able to decouple the steering interference while simultaneously transmitting information from the road surface. From the driver’s viewpoint, it is essential to ensure that a small amount of torque is transmitted to the driver. If such transmission is realized, the driver can recognize AFS operation and sense the cooperation between the steering operation and the system assisting the driver’s operation.

6.2.2 Pattern 5: velocity of reference angle $\Delta\theta^*/dt = -300(^{\circ}/s)$

The experimental result is shown in Fig. 23. The use of our control method resulted in a large hysteresis value during AFS operation.

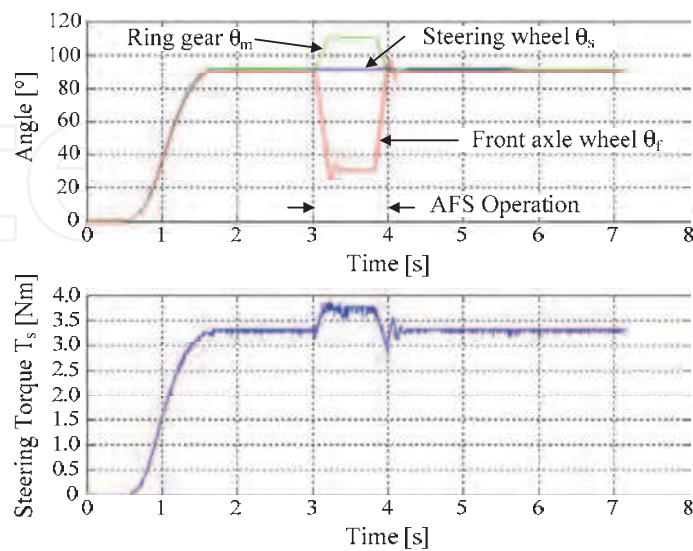


Fig. 23. Experimental result of AFS by reaction torque control based on driver sensitivity in case of pattern 5.

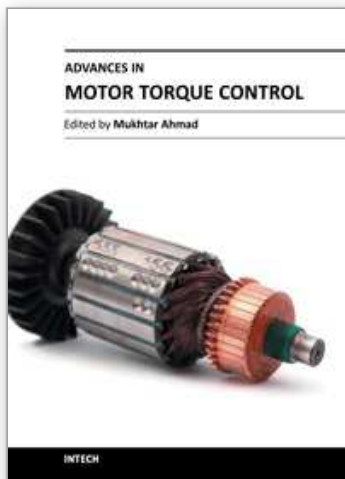
The result showed that the control reduced the steering interference while simultaneously transmitting the reaction torque from the road surface to the driver. In addition, the control reduced the steering torque vibration by adjusting the hysteresis value.

7. Conclusion

In this study, we verified the relationship between steering interference associated with AFS-assisted automatic steering and driver steering sensitivity. Drivers are very sensitive to the reaction torque, and if a driver receives it directly after it has been changed by the AFS, safe operation is impossible. Moreover, the experimental results showed that driver sensitivity is nonlinear. In particular, drivers are unable to handle a reaction torque exerted along a direction opposite to that of the torque that the driver receives from the road surface before AFS operation. Therefore, we propose a reaction torque control method based on the driver sensitivity. To be specific, the proposed method controls the gain and frequency of the reaction torque from the road surface to prevent steering interference and allow the road information required for safe operation to be transmitted to the driver. In addition, it controls hysteresis to reduce steering torque vibration. As a result, the driver can operate the steering wheel safely with AFS.

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Electric motors are widely used in industries to convert electrical energy into mechanical form. Control techniques are designed to improve the performance and efficiency of the drive so that large amounts of electrical energy can be saved. This book is primarily written with the objective of providing necessary information on use of electric motors for various applications in industries. During the last ten years a number of methods of control of electric drives have emerged. Some of these methods are described in this book. The reader will be able to understand the new methods of control used in drives, e.g. direct and sensorless control. Also the application of motor control in dentistry, the effect of human reaction and improvement of the efficiency of drives with control have been described.

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